First Symposium on OpenFOAM in Wind Energy
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The effect of moving wave on neutral marine atmospheric boundary layer

Outline

• Wind-Wave interactions
• OpenFOAM
• Studied cases
• Results
• Monin-Obukhov similarity theory

  – In neutral stability condition

\[ U_z = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \]

  – On land Atmospheric Boundary Layer (ABL)

  – Marine Atmospheric Boundary Layer (MABL)
Wind-Wave Interactions

Wind

Roughness height

Momentum

Wave

“surface wave”

Swell
nonlocal waves

Wind stress
The Wind-Wave Interactions

Wave spectrum

• When winds and waves reach equilibrium $C_p/u_\ast a \approx 30$, $C_p/U_a \approx 1.2$

• Growing sea (absorbing momentum from the wind) $C_p/u_\ast a < 30$, $C_p/U_a < 1.2$

• Old sea (giving momentum to the wind) $C_p/u_\ast a > 30$, $C_p/U_a > 1.2$
Swell effects

• Alters the wind velocity profile.
• Upward momentum transfer from ocean to the atmosphere.
• Can cause significant misalignment between winds and wind stress which invalidates the use of Monin-Obukhov similarity theory

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A LARGE EDDY SIMULATION MODEL OF HIGH WIND MARINE BOUNDARY LAYERS ABOVE A SPECTRUM OF RESOLVED MOVING WAVES, Peter P. Sullivan, James C. McWilliams and Tihomir Hristo3 (2010)
Objective

• The purpose of this study is to investigate the effect of misalignment between wind direction and wave direction on marine atmospheric boundary layer

• Using LES model in OpenFOAM to simulate the effect of resolved large scale wave on MABL.
OpenFOAM

- buoyantBoussinesqPimpleFoam
- LES
- Coriolis and geostrophic forces
  \[- \frac{1}{\rho} \frac{\partial P}{\partial x} = -fV_g \quad - \frac{1}{\rho} \frac{\partial P}{\partial y} = fU_g\]

- Wall model
  - Schumann wall model
    - \[\frac{\tau}{\langle \tau \rangle} = \frac{\langle \bar{U}_{z_1} \rangle}{\langle \bar{U}_{z_1} \rangle}\]
    - \[\langle \bar{U}_{z_1} \rangle = \frac{u_*}{\kappa} \ln \frac{z_1}{z_0}\]
    - \[\tau = \phi^{SGS} \frac{\partial \bar{U}}{\partial z}\]
• Compare with SOWFA
• (3 x 3 x 1) km
• (160 x 160 x 128) cells
• Neutral ABL
• U=15 m/s
• T=300k z<478m
• 0.5k in 62m
• 3K/m z>540
• Z_o=0.2mm
• U_g at upper boundary
• No-slip + wall model at lower boundary

OpenFOAM
U_1=9.6 m/s
u*=0.364 m/s
Averaged difference of <U> is <2%

SOWFA
10.2 m/s
0.376 m/s
Wind-wave misalignment

- Wave aligned with wind vs. 45 degrees wind-wave misalignment.
- 10 m/s neutral ABL
- Wave
  - $C_p = 7.9 \text{ m/s}$
  - $\lambda = 40 \text{ m}$
  - $a = 1 \text{ m}$
  - $a_k = 1.5$
Boundary conditions

- Domain moving with wave reference frame.
  \[ u' = u - c \quad x' = x - ct \]
- (1.2 x 1.2 x 0.8) km.
- (300 x 300 x 96) cells.
- Shallow MABL (~ 400m).
- Inversion of (0.01K/m).
- Periodic boundary conditions in horizontal direction.
- Geostrophic wind at the upper boundary.
- No-slip condition at the lower boundary.
- Spalding’s wall model.
Instantaneous pressure fluctuations

Wave aligned with wind

45 degree wind – wave misalignment
Velocity profile

The horizontally-averaged velocity profile

- 0 Degree
- 45 Degree
- Log
Instantaneous streamwise velocity fluctuation at 5m height

Wave aligned with wind

45 degrees wind – wave misalignment
Instantaneous vertical velocity fluctuation at 5m height

Wave aligned with wind

45 degrees wind – wave misalignment
Instantaneous streamwise velocity fluctuation at hub height (75m)

Wave aligned with wind

45° wind – wave misalignment
Instantaneous vertical velocity fluctuation at hub height (75m)

Wave aligned with wind

45-degree wind–wave misalignment
• Conclusion
  – Misalignment increases the turbulence intensity.
  – Misalignment decreases the velocity vertical shear.

• Future work
  – The effect of wave steepness and wave height.
  – Wave effect on stable and convective ABL.
  – Wave effect on wind turbine.
Thank you